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13. ABSTRACT *(Maximum 200 words)*

This report covers the work of the ARO/URI Center of Excellence for Composites Manufacuring Science, Reliabilty, and Maintainability Technology at the University of Delaware from 1 October 1986 through 30 November 1991. The program addressed the fundamental issues involved in the manufacturing science, reliability, and maintainability of composite structures for future Army systems. Strong emphasis was placed on building in quality, long life, predictable and reliable performance, durability, and lower life-cycle costs, with a minimum reliance on repair or rejection of poor quality after manufacturing. Material forms examined included thick-section laminates and textile woven forms; both thermoset and thermoplastic-matrix materials were investigated. An integral part of the program was the development of computer software modules to be integrated into computer models to simulate manufacturing for thick-section composites. Based on the complex interplay among processing, structure, and performance of composite material systems, the Center undertook a strongly coupled interdisciplinary approach to the development of a manufacturing science capable of producing reliable and durable products. Complementary support for the work was provided by the Center's industrial consortium. This report summarizes research accomplishments in three broad areas—*Manufacturing and Processing Sciences*, *Mechanics and Materials Design*, and *Durability*. During the five-year period, 15 graduate students were directly involved in the program as Army Fellows. Nine earned doctoral degrees during this period, and four completed master's degrees. The report documents these educational accomplaishments, as well as technology transfer efforts made under the aegis of the grant. Two inventions (patents pending) grew out of the research.

14. SUBJECT TERMS
Manufacturing Science, reliability, maintainability, thick section, durability, filament winding, residual stress, thermal stress, liquid molding, preform design.

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UNIVERSITY OF DELAWARE CENTER FOR COMPOSITE MATERIALS

FINAL REPORT TO THE U. S. ARMY RESEARCH OFFICE

CENTER FOR COMPOSITES MANUFACTURING SCIENCE, RELIABILITY, AND MAINTAINABILITY TECHNOLOGY

Co-Principal Investigators:
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Co-Investigators:

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Selçuk I. Güçeri
Azar Parvizi-Majidi
Michael T. Klein
R. Byron Pipes
John W. Gillespie, Jr.
Stuart H. Munson-McGee
Dick J. Wilkins

Program Coordinators:

Azar Parvizi-Majidi ('87) Stuart H. Munson-McGee ('88-'90) Karl V. Steiner ('91)

30 January 1992

U. S. Army Research Office

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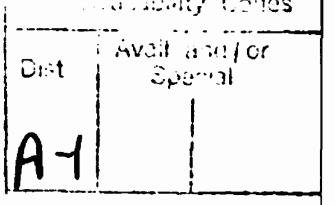
Statement of the Problem Studied

The ARO/URI Center of Excellence was established at the University of Delaware in 1986 to address the fundamental issues involved in the manufacturing science, reliability, and maintainability of composite structures for future Army systems. The program strongly emphasized building in quality, long life, predictable and reliable performance, durability, and lower life-cycle costs, with a minimum reliance on repair or rejection of poor quality after manufacturing. Research was initially conducted in the following areas:

- cure characterization and monitoring
- on-line intelligent nondestructive evaluation for in-process control
- process simulation
- computer-aided manufacturing for filament winding
- structure-property relationships of textile structural composites
- mechanics of thick-section laminates
- structural performance and durability
- integrated engineering for durable structures

The material forms examined included thick-section laminates and textile woven forms; both thermoset and thermoplastic-matrix materials were investigated. An integral part of the program was the development of computer software modules to be integrated into computer models to simulate manufacturing for thick-section composites.

Based on the complex interplay among processing, structure, and performance of composite material systems, the Center undertook a strongly coupled interdisciplinary approach to the development of a manufacturing science capable of producing reliable and durable products. Complementary support for the work was provided by the Center's industrial consortium.



Summary of the Most Important Results

Research

The five-year research program has resulted in the following accomplishments, within the broad areas outlined below (graduate students' names, followed by those of the faculty advisors, appear in parentheses):

Manufacturing and Processing Sciences

- Demonstration that molecular diffusion significantly affects the state of cure of thermosetting polymers *(graduate student: D. F. Rohr; advisor: M. T. Klein).*
- Development of stochastic modeling methods for predicting temporal and positional variations in network structure, rate of reaction and degree of cure *(graduate student: D. F. Rohr; advisor: M. T. Klein* and *graduate student: W. M. Sanford; advisor: R. L. McCullough).*
- Development and verification of a general transport model based on the unifying role of molecular

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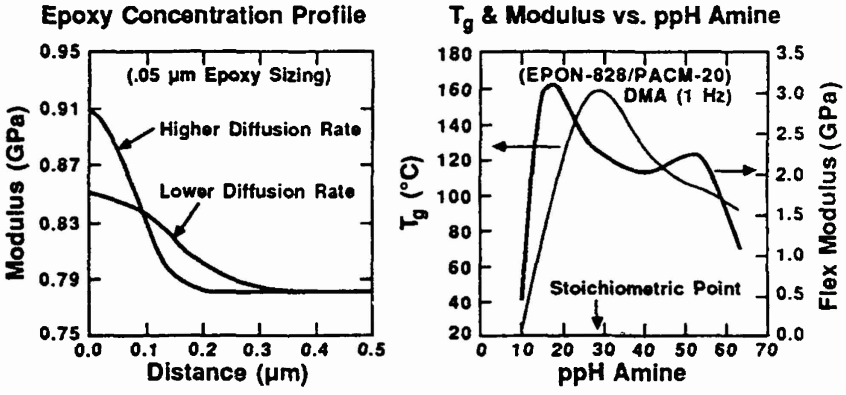
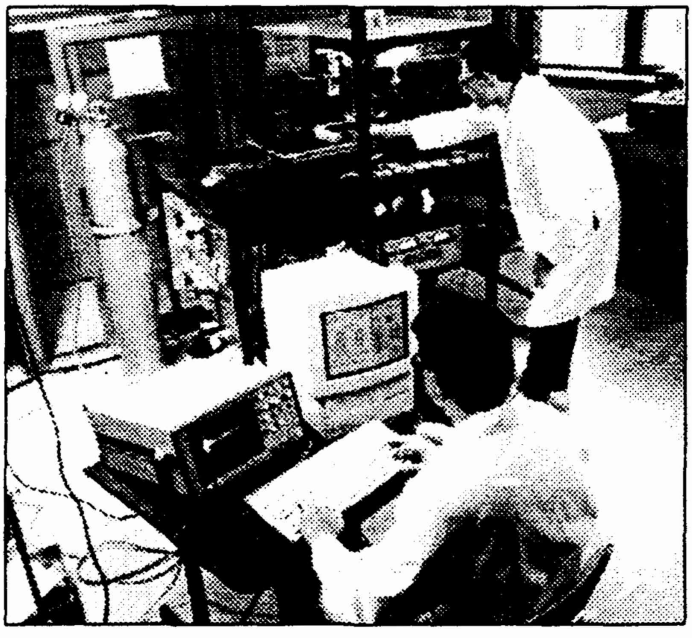
mobility which connects extent of reaction, viscosity, diffusivity, dipole relaxation, and ionic conductivity *(graduate student: W. M. Sanford; advisor: R. L. McCullough).*

- Demonstration that the general transport model provides a quantitative basis for monitoring temporal variations in the degree of cure and viscosity with local electrical sensors *(graduate student: W. M. Sanford; advisor: R. L. McCullough).*
- Development of a numerical simulation to calculate residual stress development during the nonuniform cooling of amorphous thermoplastic composites *(graduate student: S. D. Gilmore; advisors: S. I. Güçeri, J. W. Gillespie, Jr.).*
- Demonstration that property gradients of the matrix exist in the vicinity of the fiber: Thermoset property gradients result from stoichiometric imbalance due to diffusion of species to fiber surface; thermoplastic property gradients result from entropic segregation of molecular weight *(graduate student: G. R. Palmese; advisor: R. L. McCullough).*

INTERPHASE CONCENTRATION PROFILES



- Development of models to relate property gradients to local states of residual stress *(graduate student: G. R. Palmese; advisor: R. L. McCullough).*
- Experimental and theoretical investigation into textile preform joining techniques for use in the resin transfer molding (RTM) process *(graduate student: D. A. Steenkamer; advisor: D. J. Wilkins).*
- Fabrication of a variety of structural parts with different reinforcement using the RTM process *(graduate student: D. A. Steenkamer; advisor: D. J. Wilkins).*



- Design and fabrication of an automated sequential resistance welder for joining large thermoplastic parts; patent application filed *(graduate students: S. T. Holmes, S. M. Andersen* and *undergraduate student: R. C. Don; advisors: J. W. Gillespie, Jr. and C. L. T. Lambing—Alcoa).*
- Determination of the role of molecular mobility in the consolidation and bonding of thermoplastic composite materials *(graduate student: V. Agarwal; advisors: R. L. McCullough, J. M. Schultz).*
- Development and verification of a theory for the use of induction heating in fusion bonding of thermoplastic-matrix composites *(graduate student: B. K. Fink; advisors: R. L. McCullough, J. W. Gillespie, Jr.).*

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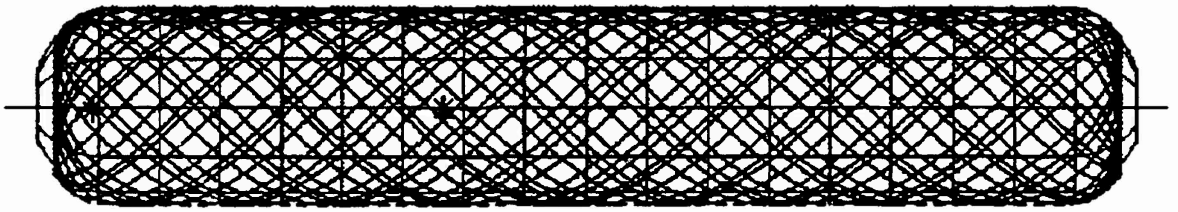
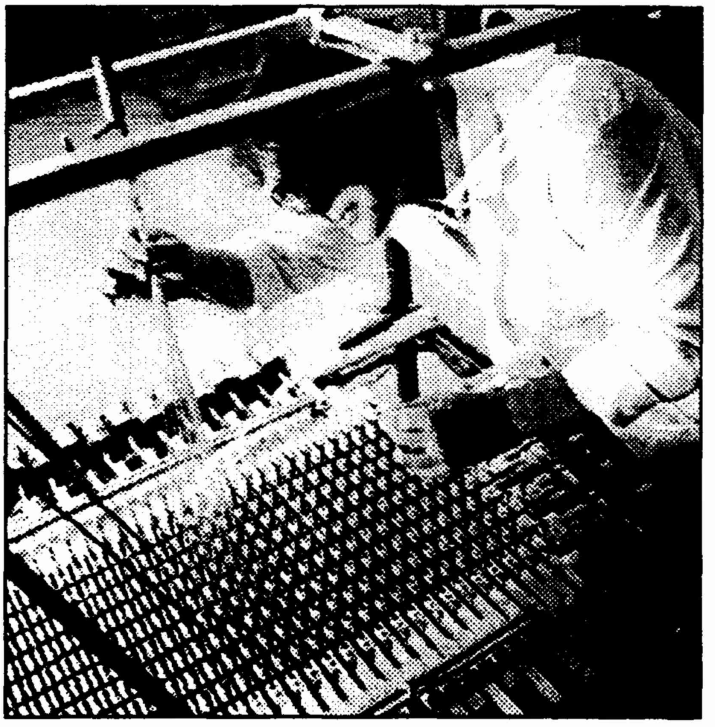
CYLINDRICAL FILAMENT-WOUND VESSEL



- Development and experimental verification of analytical models for axisymmetric and cylindrically orthotropic filament-wound shapes *(graduate student: M. Cirino, advisor: R. B. Pipes).*
- Development of a process model for the on-line consolidation of thermoplastic filament winding *(graduate student: D. R. Calhoun; advisor: R. B. Pipes).*
- Development of a computer-aided design methodology and structural mandrel optimization for filament-wound parts *(graduate student: L. M. Ahlstrom; advisor: R. B. Pipes).*

Mechanics and Materials Design

- Determination of the effects of fabric structure and material properties on the fracture resistance of thick-section textile composites, yielding information about the effect of reinforcement geometry on the strength of composites *(graduate student: S. W. Fowser; advisor: T-W. Chou).*
- Design and fabrication of automated equipment for the manufacture of three-dimensional braided preforms; patent application filed for "Braiding Machine Having Self-Propelled Bobbin Carriers" *(graduate student: T. D. Kostar; advisor: T-W. Chou).*
- Analysis of microstructure-property relationships for 3-D woven composites *(graduate student: B. LaMattina; advisor: A. Parvizi-Majidi).*
- Construction of a cure-simulation model that relates processing parameters to temporal and spatial gradients in temperature and extent of cure *(graduate student: T. A. Bogetti; advisor: J. W. Gillespie, Jr.).*
- Development of coupled chemical and mechanical models to quantify the relationships between processing conditions and the development of stress and deformation in thick-section thermosetting composites *(graduate student: T. A. Bogetti; advisor: J. W. Gillespie, Jr.).*



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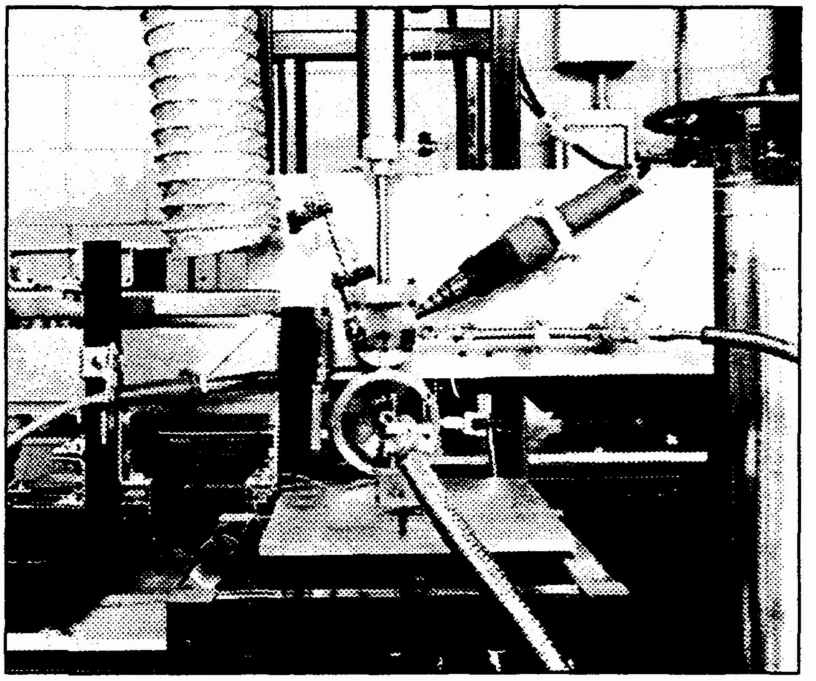
- Identification of new mechanisms for the development of residual stress and deformation in thick-section thermosetting composites *(graduate student: T. A. Bogetti; advisor: J. W. Gillespie, Jr.).*
- Demonstration that the traditional "stress-free" temperature assumption is not always appropriate for residual stress predictions in thick-section thermosetting composites *(graduate student: T. A. Bogetti; advisor: J. W. Gillespie, Jr.).*



Durability

- Development of a 3-D processing method for making comingled PEEK/graphite composites and experimental demonstration of improved resistance to impact damage for these materials over conventional 2-D reinforcements *(graduate student: L. E. Taske II; advisor: A. Parvizi-Majidi).*
- Development of a "design for impact resistance" methodology for thermoplastic composites subjected to low-velocity impact *(graduate student: T. C. Lindsay; advisor: D. J. Wilkins).*
- Development of the TQD design methodology, which uses a procedural framework to identify customer wants, converts them into quality metrics, and uses these metrics to evaluate design concepts *(graduate student: Henshaw; advisor: D. J. Wilkins).*

Education

An important objective of the ARO/URI grant to the University was to educate students in composites-related fields. The ARO/URI work was integrated into the undergraduate and graduate curricula—in particular, ME 667, *Composites Manufacturing*, and ChE 448, *Chemical Engineering Senior Laboratory*.

During the five-year period, 15 graduate students were directly involved in the program as Army Fellows. Nine earned doctoral degrees during this period, and four completed master's degrees. All of those who have completed their degrees are now working in industry, as faculty members at other academic institutions, and at Army labs. The program also supported a number of undergraduate students. One undergraduate involved in the work has also gone on to work at an Army lab and is planning to initiate graduate work at the University as an Army employee. Through interaction with the Army Fellows via the Center's ongoing interdisciplinary research and education programs, an additional 60-plus students have both had input into the Army program and been influenced by its output.

Another educational highlight that has emerged from the five-year ARO/URI program is the emergence of

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the University of Delaware as the institution of choice for graduate studies in composites-related fields. Seven Army employees have recently worked on advanced degrees here, with others planning to initiate studies in the near future. A cyclical relationship has evolved, with Army employees studying at the Center and University alumni selecting the Army as an employer following graduation.

ARMY PERSONNEL AT CCM

Personnel	Prior Assignment	Dept./Program
Cpt. Bruce Fink	Korea	Materials Science
Mr. David Hopkins	BRL	Mechanical Eng'g
Maj. Tim Lindsay	Picatinny Arsenal	Materials Science
Lt. Col. Len Ogborn	TACOM	Mechanical Eng'g
Cpt. James Parker	Ft. Knox	Materials Science
Dr. Ned Patton	BRL	Mechanical Eng'g
Dr. Bill Walters	BRL	Visiting Scientist

Technology Transfer

The productivity of the ARO/URI program at Delaware can be measured quantitatively through technology transfer efforts. The work has been documented in more than one hundred technical articles, conference proceedings, presentations in the U. S. and abroad, internal reports, and satellite presentations. The findings have been published in a number of refereed journals, including *Composites Science and Technology*, *Composites Manufacturing*, *Computers and Structures*, *International Journal of Fracture*, *Journal of Applied Mechanics*, *Journal of Composite Materials*, *Journal of Materials Science*, *Journal of Polymer Science*, *Numerical Heat Transfer*, and *SAMPE Journal*.

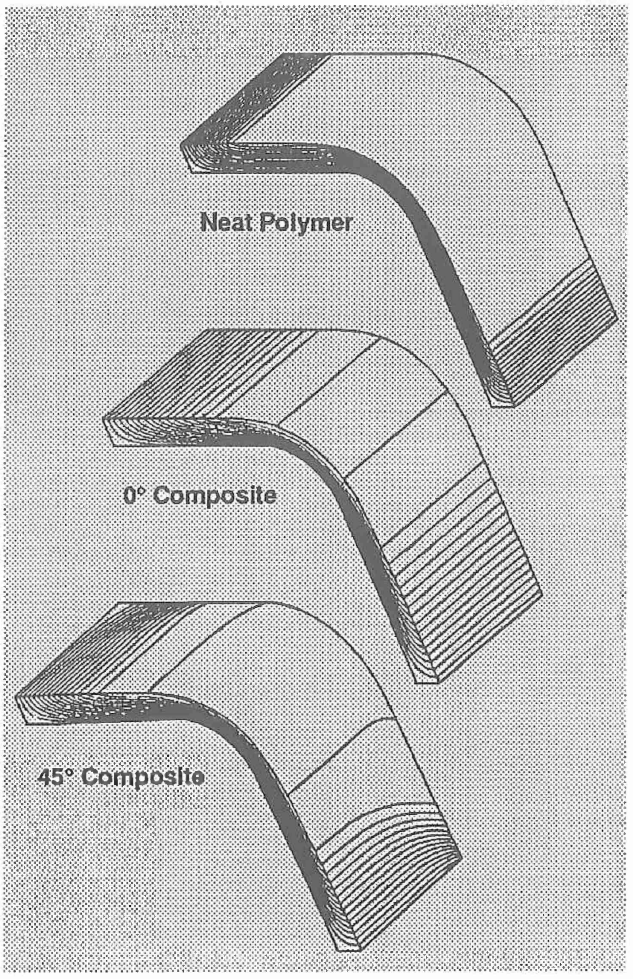
The Center's continuing education programs have also proved highly valuable to the Army. Some 120 Army representatives attended the Center's annual composites workshops and research symposia during the past five years, with additional interactions occurring on an informal basis throughout the year at both the Center and Army labs. Army employees were also offered access to the *Delaware Composites Design Encyclopedia*, the interactive videodisc course *Experimental Mechanics of Composite Materials*, the professional development videotape series *Introduction to Composites*, and the Center's many seminars, research reviews, and poster sessions.

TECHNOLOGY TRANSFER ACCOMPLISHMENTS

- **Established an effective communications network with Army laboratories.**
  - Aberdeen Proving Ground
  - AMC
  - ARO
  - Belvoir R&D Center
  - BRL
  - MICOM
  - MTL
  - TACOM
- **Developed computer software to assist Army program.**
  - CMAP
  - CMAPNL
  - LIMS-G
  - PLYDROP
  - PIRSA
  - SMC
  - STIF3D
  - TGCURE
  - TGDRAW
  - TGMESH
  - WFM
- **Issued 240 reports.**
- **Published 513 archival papers.**
- **Held 5 Workshops and 5 Symposia with more than 120 Army attendees.**
- **Published and distributed 6-volume *Delaware Composites Design Encyclopedia*.**
- **Authored and edited 21 books.**

A cure simulation software package, TGCURE, was also developed as an outgrowth of the program. TGCURE integrates many of the results from various projects to simulate the curing process of thermosetting

composite parts of arbitrary cross-sectional geometry. Temperature, degree of cure, and relative viscosity distributions are calculated as a function of autoclave temperature cure cycle history. The boundary fitted coordinate system (BFCS) transformation, combined with the alternating direction explicit (ADE) finite difference method, is used to numerically solve the governing equations. Anisotropic heat transfer effects are included in the analysis. Required input includes part geometry, autoclave temperature cure cycle history, effective part geometry boundary conditions, thermal properties, and reaction kinetics parameters.



Facilities

The Center of Excellence grant included a $1-million initial equipment allocation. During the grant period, the Center's 34,000-square-foot Composites Manufacturing Science Lab was completed (1988), with funding from the State of Delaware and industry. Completion of the building consolidated the Center's research capabilities—a direct benefit to the Army as well as an outgrowth of the grant itself.

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ARMY ATTENDANCE AT CCM'S ANNUAL SYMPOSIA AND WORKSHOPS

Symposium Year	Number of Attendees	Representing How Many Labs
1991	16	5
1990	20	5
1989	11	5
1988	7	
Workshop Year	**Number of Attendees**	**Representing How Many Labs**
1991	20	5
1990	33	8
1989	12	6

List of All Participating Scientific Personnel

Faculty/Professional Staff

Antony N. Beris
Robert A. Blake
Tsu-Wei Chou
John W. Gillespie, Jr.
Selçuk I. Güçeri
Michael T. Klein
Azar Parvizi-Majidi
Roy L. McCullough
Stuart H. Munson McGee
R. Byron Pipes
Karl V. Steiner
Dick J. Wilkins

Students

Vivek Agarwal
Lee M. Ahlstrom
Travis A. Bogetti
Daryl R. Calhoun
Mark Cirino
David L. Fecko
Scott W. Fowser
Scott D. Gilmore
John M. Henshaw
Scott T. Holmes
Richard G. Irwin, Jr.
Timothy D. Kostar
Bruce LaMattina
Eric J. Lang
L. Peter Martin
Eric M. Orndorff
Giuseppe R. Palmese
Christopher L. Pederson
Donald F. Rohr
W. Michael Sanford
Stephen F. Schuler
David A. Steenkamer
Leo E. Taske II

Report of Inventions

"Automated Resistance Welding Machine" (C. L. T. Lambing, Alcoa; S. M. Andersen, R. C. Don, J. W. Gillespie, Jr., S. T. Holmes, and B. S. Leach) 1989.

"Braiding Machine Having Self-Propelled Bobbin Carriers" (T. D. Kostar and G-W. Du) 1990.

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List of All Publications and Technical Reports

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Byun, J-H., T. J. Whitney, G-W. Du, and T-W. Chou, "Analytical Characterization of Two-Step Braided Composites," *Journal of Composite Materials*, 25, pp. 1599-1618, 1991.

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Gillespie, J. W., Jr., R. L. McCullough, and R. F. Eduljee, "On the Application of Micromechanics to Predict Macroscopic Thermal Residual Stresses in Short Fiber Reinforced Polyetheretherketone," *Polymer Engineering and Science*, 31(7):1257-1263, 1991.

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Karbhari, V. M. and D. J. Wilkins, "Metrics and Scales of Comparison - Links Between Design and Manufacturing of Composites," to be published in the *International Journal of Materials and Product Technology*, Vol. 6. No. 4, 1991.

Karbhari, V. M., J. M. Henshaw, D. J. Wilkins and S. H. Munson-McGee, "Composites Design, Manufacturing, and Other Issues: A View Towards the Future," submitted to the *International Journal of Materials and Product Technology*.

Karbhari, V. M., J. S. Burns, and D. J. Wilkins, "Total Quality Design: An Approach for Customer Satisfaction in Critical Advanced Technologies," submitted to *Engineering Management*, 1991.

Karbhari, V. M., S. G. Slotte, D. A. Steenkamer, and D. J. Wilkins, "Effect of Material, Process, and Equipment Variables on the Performance of RTM Parts," submitted to *Composites Manufacturing*, 1991.

Lindsay, T. C., "Improving Technology Transition with Total Quality Design (TQD)," accepted for publication in *Army RD&A Bulletin*, March-April, 1991.

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1991

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Byun, J-H. and T-W. Chou, "Microstructure and Process Characteristics of 3-D Braided Preforms," *Proceedings of the Eighth International Conference on Composite Materials (ICCM/8)*, Honolulu, HI, July 15-19, 1991. SAMPE: Covina, CA.

Byun, J-H. and T-W. Chou, "Stress-Strain Behavior of 3-D Braided Composites," *Proceedings of the ASME Winter Meeting on Composites in Transportation Vehicles*, Atlanta, GA, December 1-6, 1991.

Byun, J-H. and T-W. Chou, "Microstructure-Process-Performance Relationships of 3-D Textile Composites," CCM University-Industry Research Symposium, September 24-26, 1991.

Fink, B. K. and J. W. Gillespie, Jr., "Heating of Carbon-Fiber-Reinforced Thermoplastic Composites by Magnetic Induction," CCM University-Industry Research Symposium, September 24-26, 1991.

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